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Charge structures interaction in low temperature STM surface investigations

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Abstract. In this work we present the results of low-temperature STM investigation of $A_{III}B_V$ semiconductors surface in situ cleaved along (110) plane. On topographic STM images we have found surface charge structures. The possibility of their observation depends on the STM tip apex charge state. We have observed peaks in local tunneling conductivity spectra. Energy position of these peaks as well as the energy position of band gap edges changes with distance from the defect. Experimental data points to the existence of interacting induced charges localized both on STM tip apex and defects on the surface or in nearest subsurface layers.

With accumulation of experimental data the correspondence of experimental tunneling conductivity spectra and unperturbed sample electron density of states become of great importance [1]. This problem is especially actual with temperature decreasing when tunneling and relaxation rates can be comparable [2]. As it was shown in [3] non equilibrium electron distribution can occur. Such distribution leads to the appearence of tunneling bias voltage dependent localized charges. In present work we show the importance of localized charges mutual influence by means of STM/STS investigation of clean GaAs monocrystals (110) surface.

All STM measurements were carried out using home build low temperature STM with in situ sample cleavage mechanism [4] at temperature 4.2 K. Heavily doped ($n \simeq 5 \times 10^{17}\,\mathrm{cm}^{-3}$) with tellurium semiconductor GaAs crystals have been investigated in our experiments. Electrical ohmic contacts were deposited by thermodiffusion method on specially cut samples. Samples were cleaved along (110) plane after cooling down to 4.2 K in pure He atmosphere. This procedure provided clean surface for at least 10 days. Because of relatively low samples conductivity STM measurements were carried out with tunneling current values in 10 pA range. Spectroscopic data was obtained by means of Current Imaging Tunneling Spectroscopy (CITS). Tunneling conductivity curves averaging over surface area gives high signal to noise ratio for numerical evaluation of differential conductivity spectra.

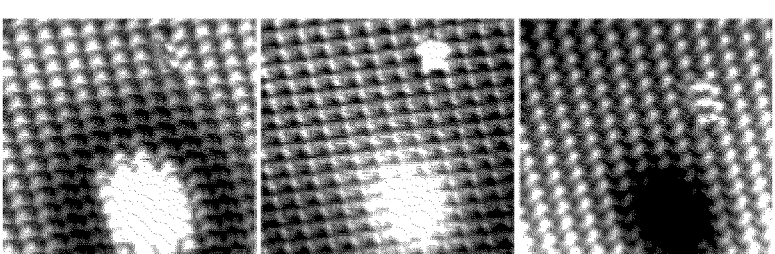

Fig 1. Topographic STM images of tellurium atom on (110) GaAs surface at temperature 4.2 K. Area 5.8×5.8 nm, tunneling current 20 pA. Tunneling voltage: (a) −1.5 V; (b) +1 V; (c) +0.5 V.

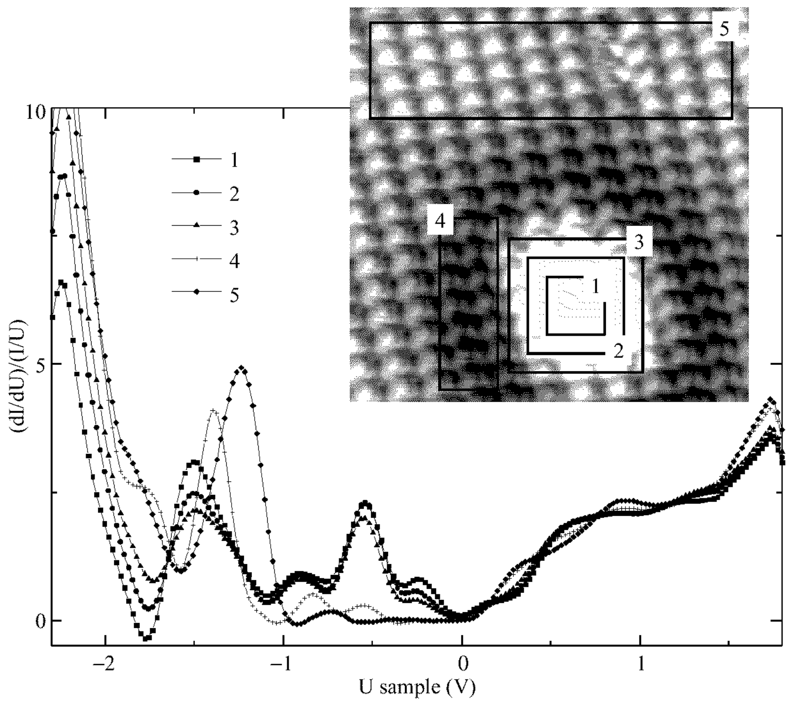

Fig 2. Tunneling conductivity spectra near tellurium atom on (110) GaAs surface at temperature 4.2 K. Insert depicts the image of surface area 5.8×5.8 nm in size where spectroscopic data was acquired. Each curve is the result of averaging over surface area which is marked by numbers.

For clear understanding of experimental results the direct comparison of surface defects topographic STM images at different values of tunneling bias voltage with local spectroscopy data is of great interest. Topograms of GaAs surface near the defects are depicted in Fig. 1. According to the common view [5] such type of defect is doping atom residing on the surface. Note some specific features of these images. STM image of doping atom is about 2 nm in diameter. The contrast of dopant image changes with variation of tunneling bias voltage from +1 V to +0.5 V. At negative sample bias the dark ring appears around impurity atom.

We suppose that topographic images behaviour is determined by charge effects which is confirmed by the shape of normalized density of states curves presented in Fig. 2. Each curve is the result of averaging over surface area which is marked by numbers on the insert. Let us mention the main features of tunneling conductivity curves. First, the measured band gap edges position near the defect differs from its flat surface region value. Second, the set of peaks around the defect exists in voltage range from −1 V to 0 V, which is absent above flat surface. Third, there is tunneling conductivity peak in the bias range −1.5 V to −1 V. The position and height of this peak depend on a distance from the defect.

It is obvious that charge interaction strongly depends on the distance between charges. Fig. 3. depicts topograms and spectroscopic data measured near impurity atom in the second subsurface layer. Contrary to STM images of surface impurity subsurface atom image does not change its contrast. At the same time the ring structure

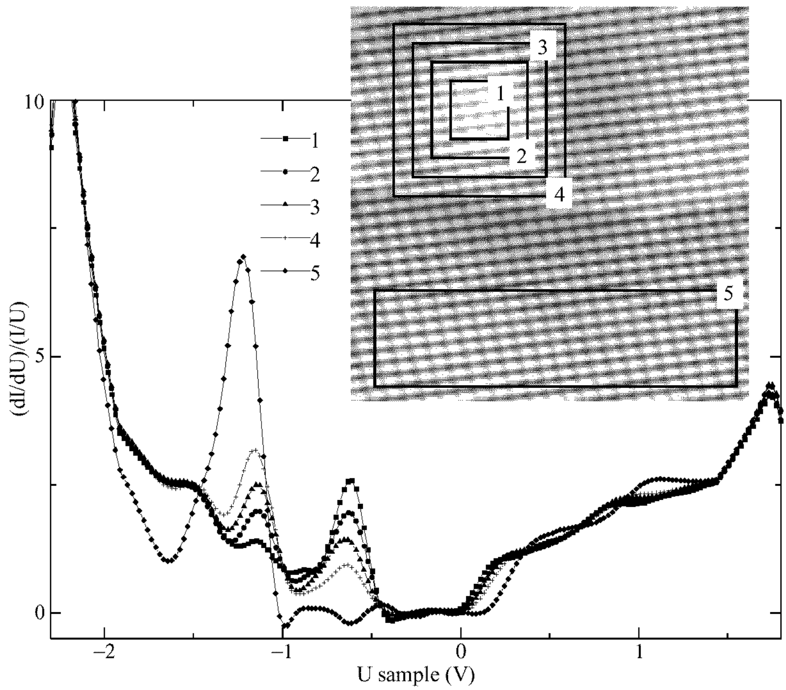

Fig 3. Tunneling conductivity spectra near tellurium atom in second subsurface layer at temperature 4.2 K. Insert depicts the image of surface area 7.3×7.3 nm in size where spectroscopic data was acquired. Each curve is the result of averaging over surface area which is marked by numbers. Tunneling current 20 pA, tunneling voltage −1.5 V.

still exists.

Tunneling conductivity behaviour also differs in the case of subsurface defect. There are peaks near the defect as it was before, but the energy position of the peaks does not change with the distance from the defect. The amplitude of one peak (around −1.2 V) increases while the amplitude of another one (around −0.7 V) decreases with increasing of the distance from the defect. The first one become dominant above flat surface.

We consider that tunneling conductivity peaks in band gap can be connected with Coulomb interaction of doping atoms states and induced charges, localized on STM tip apex. As it was shown in [6] on site Coulomb repulsion of localized electrons of Hubbard type is very important. Such interaction can considerably change the energy values even for deep impurity levels. As a result strong dependence of level energy on tunneling bias voltage appears.

Experimentally measured tunneling conductivity peak position does not coincide with the bulk value of unperturbed doping impurity energy levels. Experimentally obtained tunneling conductivity is not determined by simple convolution of sample and tip densities of states, especially if finite relaxation rate of nonequilibrium electrons is taken into account.

Another remarkable example of charge effects existence is Friedel oscillations observation near isolated charged defect. If the distance between neighbouring defects

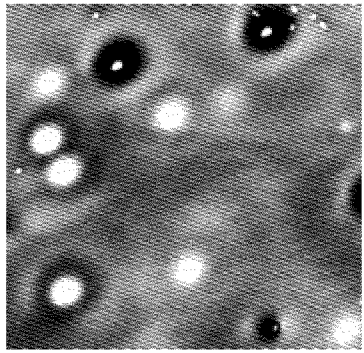

Fig 4. Topographic STM images of (110) GaAs surface area at temperature 4.2 K. Area 41×41 nm, tunneling current 40 pA. Tunneling voltage −1.5 V. Image gray scale corresponds to 0.05 nm.

is comparable with screening length (about 10 nm in case of GaAs) superposition of Friedel oscillations from different defects can appear. So nontrivial charge structures can be formed on the sample surface (Fig. 4). For GaAs tip-sample separation (about 0.5 nm) does not exceed the radius of enhanced charge area around the defect (more than 2 nm). So, the induced charge on STM tip apex plays the same role as the defect charge. Thus the charge states on the tip modifies experimentally observed distribution of electron density and corresponding STM image of Friedel oscillations. Apparently this is a reason why STM images on Fig. 4 and Fig. 1 are different. On the last one only one the most intensive ring is visible.

In conclusion, experimental STM/STS data are strongly influenced by induced charge interaction which considerably modifies initial unperturbed sample density of states.

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